# GEMS: A Revolutionary System for Environmental Monitoring

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## ABSTRACT

This paper describes a revolutionary, new observing system designed for environmental monitoring that will integrate MicroElectroMechanicalSystems (MEMS) and nanotechnologies. The concept, known as Global Environmental MEMS Sensors (GEMS), features an integrated system of airborne probes that will remain suspended in the atmosphere for hours to days and take measurements as they are carried by wind currents. Previous efforts focused on defining the major feasibility issues associated with system design and development in the decadal time frame. The current 2-year project focuses on studying the major feasibility issues including costs/benefits and developing a technology roadmap.

***Keywords***: environmental monitoring, airborne probes, microelectromechanical systems, nanotechnology

## 1 INTRODUCTION

Technological advancements in MicroElectro MechanicalSystems (MEMS) and nanotechnology have inspired a revolutionary, multi-purpose observing system known as Global Environmental MEMS Sensors (GEMS). The GEMS concept features in situ, micron-scale airborne probes that can monitor all regions of the Earth with unprecedented spatial and temporal resolution.

The probes will be designed to remain suspended in the atmosphere for hours to days and take measurements of pressure, temperature, humidity, and wind velocity as they are carried by atmospheric currents. Once the probes settle out of the atmosphere, they could continue taking surface measurements over land or water. In addition to gathering meteorological data, the probes could be used for monitoring and predicting the dispersion of particulate emissions, organic and inorganic pollutants, ozone, carbon dioxide, and chemical, biological, or nuclear contaminants. GEMS could also be modified for use in a variety of defense applications including intelligence gathering and space situational awareness as well as aid in space and planetary exploration [1].

A phase I proof-of-concept effort funded by the NASA Institute for Advanced Concepts (NIAC) in May 2002 focused on validating the viability of GEMS and defining the major feasibility issues related to system design and development [2]. The goal of the 2-year, phase II project, which began in September 2003, is to study the major feasibility issues in detail, examine the potential performance and cost benefits of the system, and develop a technology roadmap that NASA could use to integrate GEMS and its enabling micro and nanotechnologies into future missions and programs in the decadal time scale. An experiment is also planned in late 2004 to demonstrate the deployment of a sample network of airborne probes, built from commercial-off-the-shelf hardware and software. This paper highlights results from the phase I project and describes the details for studying the meteorological and engineering issues during the phase II effort.

## 2 DESCRIPTION

GEMS consist of an integrated system of MEMS-based probes that are envisioned to be mass-produced at very low per unit cost. Based on specific applications, the probes will be as small as 50–100 microns in one or more dimensions and lightweight enough to pose virtually no danger upon contact with persons or property. The blending of materials science and biology could produce new materials that significantly limit probe mass and potentially make them biodegradable or bioinert. Continued advancements in materials science and nanotechnology could pave the way for the design and development of morphing probes that could change shape using smart materials and structures. Such morphing capabilities may enable larger probes to remain airborne for longer periods of time.

The evolutionary successes found throughout nature suggest that nanobiotechnology be explored as a possible means to design and create micro and nanoscale components for the system. Nanobiotechnology merges biological systems with nanofabrication through the creation of tools that enable researchers to better understand how organic cells function. This knowledge can open a door for mimicking and integrating proven biological cellular devices and components into probe designs [3].

The size, mass, aspect ratio, component geometry, buoyancy control, and aerodynamic design will all determine how long probes remain airborne. Buoyancy control could be the most effective way to reduce the terminal velocity of probes and keep them suspended for much longer periods of time. Recent work by [4] and [5] demonstrated that hydrogen storage on nanocrystalline materials may be used to regulate buoyancy. Depending on the size and shape of the probes, aerodynamic design could also reduce their ballistic coefficient and terminal velocity.

Many examples of such design exist in the natural world, including simple dandelion spokes and threads of balloon spiders, as well as sophisticated evolved forms like auto-rotating samaras [6].

The probes will be capable of sensing a number of parameters including temperature, moisture, pressure, velocity, chemical/biological compounds, and radiation. Microfabricated devices for sensing temperature, humidity, and pressure are well developed [7]. Atmospheric wind velocity will be measured based on changes in probe position that will be determined using global positioning system-aided inertial navigation systems and network localization. With network localization, only several probes have knowledge of their locations and the remaining ones estimate their relative positions dynamically using on-board algorithms [8]. There has been a recent surge in microcantilever research for high-sensitivity chemical, biological, and radiation sensing [9]. In most cases, these existing technologies can be modified for integrated, low-power applications such as GEMS.

In a step towards their ultimate goal of 1-cubic millimeter wireless devices [10], University of California Berkeley researchers integrated a radio transmitter, sensor interface electronics, microprocessor, and memory into a single silicon chip measuring 5 mm$^2$ (Fig. 1). Single-chip integration of communication, sensing, and computation reduces the cost per device since post fabrication steps can be eliminated. A continued decrease in size and cost through mass production provides ample opportunities for low-cost deployment of large numbers of probes.

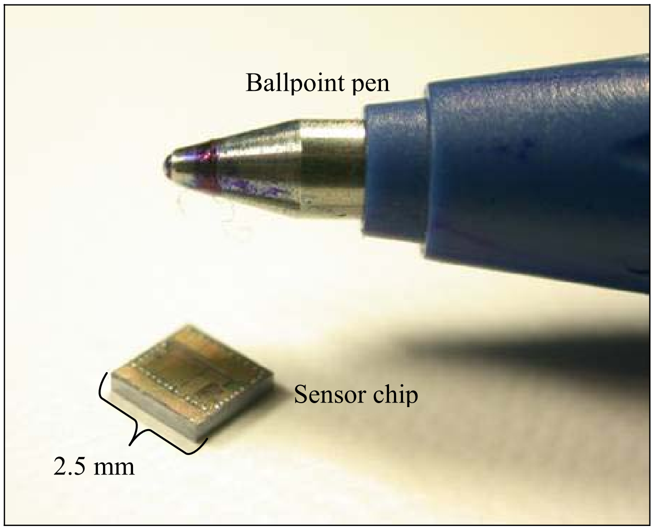

Figure 1. Sensor chip for the latest generation of wireless devices from University of California Berkeley.

The probes will communicate with other probes, intermediate nodes, data collectors (i.e. “mother ships”), and remote receiving platforms using radio and optical frequency transmissions to form a wireless, mobile, in situ network (Fig. 2). As part of a wireless network, the probes will not require recovery to collect data and therefore will be disposable. The data collectors are envisioned to be larger than individual probes and distributed throughout the atmosphere. There will likely be intermediate nodes in the hierarchy as well, capable of longer-range communication and/or more data processing than the individual probes, but still autonomous. The largest data collectors are envisioned to be a series of ground- and space-based receiving platforms that relay data from the intermediate nodes and provide a means to acquire and process data within wired regional and/or global terrestrial networks.

Figure 2. GEMS conceptualization illustrating possible probe design, deployment, dispersion, communication, and networking.

Deployment of GEMS is envisioned from both ground sites and airborne platforms such as aircraft, unmanned aerial vehicles, conventional weather balloons, and high altitude balloons [11]. There are numerous scenarios where high spatial and temporal resolution data from GEMS would be valuable to assess the potential for and development of high impact weather such as tornadoes, severe thunderstorms, and hurricanes, or to support special operations in data limited or data denied regions.

## 3 PHASE I: KEY ISSUES AND ENABLING TECHNOLOGIES

The phase I project focused on defining the major feasibility issues and determining the primary enabling technologies that must be clearly addressed for the future design and development of GEMS. A framework was also established for an interdisciplinary simulation-design-test (SDT) cycle that will be used extensively in phase II as part of detailed cost-benefit analyses to study the major feasibility issues. A summary of the key issues and enabling technologies is presented in Table 1 along with selected results from the phase I study. More details are available in [2].

| Major Feasibility Issues | Primary Enabling Technologies |
|---|---|
| Probe design | Materials science, nanotechnology, biomimetics |
| Power | Batteries, micro fuel cells, solar energy |
| Communication | MEMS-based radio frequency and/or free-space optical systems |
| Networking | Artificial intelligence (autonomous self-healing networks) |
| Measurement | MEMS-based sensors |
| Data collection/management | Artificial intelligence, data mining |
| Cost | MEMS mass production/packaging, deployment strategies, data collection infrastructure |

Table 2. Key issues and enabling technologies affecting GEMS design and development.

Several critical issues were identified in phase I relating to probe design. Power for the probes will likely come from a combination of batteries, fuel cells, and solar energy. Fuel cells are a very promising long-term solution for autonomous system power generation because their energy densities are dramatically higher than that of batteries. Both battery and fuel cell operation present a challenge at the colder temperatures in the upper atmosphere.

The probes will have to be robust enough to ensure that the electronics are isolated from the effects of liquid and frozen water, dust, chemical pollutants, radiation, and static electricity so MEMS packaging is an issue [12]. It will also be necessary to shield the sensors from the electronics so that they are not affected by thermal noise in the circuits.

At a minimum, the probes will need to communicate with some form of data collection nodes. If probe communications are handled using active Radio Frequency (RF) transmissions, the power requirements are projected to be 100 times greater than free-space optical communication. Communication from airborne probes using optical frequencies can have some advantages over RF due to the high antenna gains available when the wavelength is small; however, optical signals cannot penetrate dense cloud cover.

The issues related to probe deployment and dispersion were explored using a numerical weather prediction (NWP) model coupled with a Lagrangian particle model (LPM). To study probe deployment and dispersion over larger spatial and temporal scales, the models were configured to run over most of the northern hemisphere for a period of 24 days, and simulate probe release from a hypothetical network of high altitude balloons. This simulation demonstrated that atmospheric circulation patterns can disperse probes throughout the northern hemisphere in just 10 days with such a deployment scenario.

Observing system simulation experiments (OSSEs) were used to assess the impact of simulated probe data on forecasts of a selected weather event within a regional domain. The assimilation of simulated probe data resulted in a substantial reduction of forecast errors and improvements in predicted precipitation patterns. Excluding temperature, moisture, or wind data in the OSSE framework significantly degraded the model forecast not only for the parameter excluded, but for the precipitation forecast as well. This sensitivity test indicated that, at least for the case studied, the maximum data impact resulted when GEMS provided a full suite of temperature, moisture, pressure, and wind measurements.

# 4 PHASE II DEVELOPMENT PLAN

Pursuit of the GEMS concept is necessarily interdisciplinary, guided by realistic projections of progress in the miniaturization of probe components and demonstrable improvements in weather forecast accuracy by simulated meteorological observations from a mobile network of airborne probes. Interdisciplinary collaboration is the key element of the SDT cycle, quantifying trade-offs between weather forecast impacts and probe characteristics. The large number of possible trade-offs based on design characteristics such as sensor accuracy and sampling frequency, weather scenarios, and other factors constitute a multi-dimensional parameter space. Because of the high dimensionality and complexity of the parameter matrix, it is not reasonable to attempt a mechanical examination of every possible combination and permutation. Instead, extensive use will be made of modeling in the SDT cycle as a cost-effective and controlled way to explore the trade-offs, mapping out logical and self-consistent pathways for further detailed exploration. An overall system model of GEMS will be formulated in phase II following guidelines for systems engineering that will link together results from the component SDT cycles and provide a pathway for developing a technology roadmap. The system model will facilitate understanding how changes in one subsystem will affect other subsystems and the cost-benefit of the system.

## 4.1 Meteorological Issues

The meteorological portion of the development plan will include two parts. The first part will study probe dispersion and resulting distributions for several potential deployment strategies on a hemispheric scale. The second part of the meteorological plan will use the OSSE framework to study the data impact issues. A number of potential deployment strategies will be explored including probe release from high-altitude balloons, surface stations assuming positive buoyancy, manned/unmanned aircraft for targeted observations and vertical profiles similar to weather balloon measurements. Each of these deployment strategies will be simulated using the NWP/LPM models on a hemispheric scale. A comprehensive analysis of the resulting dispersion patterns will be conducted for variations of each deployment scenario. This analysis is critical to understand the scientific feasibility and cost practicality of each scenario.

The second part of the meteorological development plan will consist of regional data-impact analyses of specific deployment scenarios using OSSEs. OSSEs have been conducted for decades in meteorology to evaluate the potential impact of proposed remote and in situ observing systems, determine trade-offs in instrument design, and evaluate the most effective data assimilation methodologies to incorporate the new observations into regional and global NWP models [13].

## 4.2 MEMS and Engineering Issues

The major MEMS and engineering issues identified in Table 1 will be studied by focusing on physical limitations for measurement and signal detection based on fundamental and technical noise sources, scaling as the individual probes become smaller and the number of probes in the network becomes larger, and disciplined engineering optimization of the trade-offs which affect the cost, practicality, and feasibility of the overall system.

A detailed cost-benefit analysis will be performed to explore the costs associated with building and implementing GEMS, weighed against the benefits derived from the improved weather forecasts that will result from the data. Included in this cost analysis will be a quantitative comparison of GEMS with future observing systems.

When assessing the economic value of weather forecasts, [14] advocated a multidisciplinary approach that includes meteorology, economics, psychology, statistics, management science, and operations research. Likewise, the cost of the GEMS will vary based on the established requirements of achieving certain levels of data collection. These levels include, but are not limited to, probe density in space and time and measurement accuracy. Probe costs will also be driven by the engineering and manufacturing challenges discussed previously.

## 5 SUMMARY

This paper describes a new, in situ observing system known as Global Environmental MEMS Sensors (GEMS) that features airborne probes suspended in the air for hours to days. Results from the first phase of the project focused on identifying the major feasibility issues and key enabling technologies necessary for system development. The goals of the phase II project are to study these issues in detail including cost/benefits and development time and construct a technology roadmap. The presentation at the conference will highlight progress during the first 6 months of the phase II effort highlighting simulated probe dispersion and deployment scenarios, power budgets, and limitations of micromachined circuits and sensors for this application.

## 6 ACKNOWLEDGEMENTS

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